REVIEW PAPER

TRENDS IN SIMULATION TECHNOLOGIES FOR AIRCRAFT DESIGN

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Abstract

The developments in flight simulation since its inception are reviewed and the latest trends in the use of modeling and simulation for design of flying vehicles are presented. Mathematical model based system development is now universally recognized as a cost effective way to bring new design concepts into reality. The efforts made at CSIR-NAL in this regard over the years are also described in brief. The design of systems which require scenario based evaluation like the flight control system and avionics benefit from the use of a reconfigurable simulator developed concurrently with the aircraft. A reconfigurable simulator allows for rapid prototyping of the systems during the design phase in an integrated environment. Ideas for the implementation of Systems Engineering concepts in new and existing aircraft programs using mathematical models are discussed.

Introduction

The history of flight simulators began with an attempt to give pilots a feel for the cockpit, navigation, instrument flying, interaction with other aircraft and included &-to-air gunnery [1]. These simulators were platform specific, supporting operational requirements and training of the operator. An early example of this is the early roll coupling experiment conducted at Dryden Flight Research Center in 1955 on a NACA analog computer for the Bell X-2 [2]. The development of digital fly-by-wire in the 1960's led to the need for hardware in the loop testing in addition to other flight hardware.

A modern simulator uses mathematical models of the aircraft and systems with visuals to provide the trainee pilot a realistic look and feel of the aircraft. The quality of the visuals available now approaches the resolution limit of the human eye. The high fidelity of the mathematical models now permits a Zero Flight Time Training (ZFTT) approach where a trainee pilot can begin flying the aircraft immediately after his simulator training is over. This provides for saving in terms of costs and enhanced safety. In addition to the flight crew, simulators can also be designed for the ground crew involved in maintenance. Virtual reality concepts are being used to study the ergonomics of the aircraft layout for ease of maintenance [3].

Other simulators were built to provide a developmental and training environment for the engineers. These simulators supported development of aircraft operational concepts and flight testing. The engineering simulators helped in the development of new platforms which took concepts from requirements to reality [4-5]. These simulators include the use of desktop and specialized simulators to allow the engineers and the customer to get a look at how a new design might function before the detailed design stage. At this stage in the design, the engineer or customer may be interested in evaluating different aircraft configurations to meet the overall mission objective. Therefore, the simulator framework must allow for rapid change over of the mathematical models between the different aircraft configurations. If the framework is custom made for each configuration, this results in time consuming rework for every change over. Thus, the ability to reconfigure the simulator quickly is essential to reduce the time taken to implement or demonstrate competing ideas for the same mission [6]. The in-flight simulator is an extreme example of a reconfigurable simulator for flight control system development and testing [2]. The development of Integrated Enhanced and Synthetic Vision Systems (IESVS) can benefit greatly from the use of simulation tools during the design and development phase. Simulators have been used effectively to answer questions on the design trade-offs as well as operational issues of

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using these systems. They can also be used to test the Concept of Operation (CONOPS) for the pilots and ground based operators of the aircraft. SIMONA is an example of a research simulator for human-machine interaction studies build at the Delft University in the Netherlands [7].

The V-22 Osprey [8], Joint Strike fighter [9] and Saab Gripen [10] programs have all benefitted from the use of an engineering simulator. An engineering simulator is typically used for analyzing and verifying system design. Therefore, a simulator of this nature will have mathematical models and hardware of a fidelity level suitable to take design decisions at the preliminary design stage. In India, the Light Combat Aircraft [11] and Advanced Light Helicopter programs have provided a major boost to the development of engineering simulators. On the military side, the network centric paradigm is of particular importance. The development of Distributed Interactive Simulation (DIS) and later high Level Architecture (HLA) has promoted the ability to connect one simulator to many others leading to the ability to simulate multi-vehicle interactions in a realistic manner, thereby promoting realistic training for complex, multi aircraft combat Mission training [12]. Attempts have also been made to create realistic (Live, Virtual and Constructive or LVC) scenarios which simulate live flight assets, ground based simulators and digitally generated platforms in an interactive manner.

The large scale and distributed simulation have been used effectively in the civil aircraft design simulators. Programs like the Pilatus [13], ERJ 170 [14], Boeing 777 [15] have all used the power of flight simulation early in the design cycle to identify and correct many problems and issues prior to flight testing. Typically, in the early design stage, simulation and testing helps to identify problems in the design of a system, integration between various systems and spot potential certification issues before these aircraft are flight tested. Traditionally, due to the complexity and cost of building large scale integration rigs, many of the airplane subsystems could not be tested in a fully integrated manner on the ground. The Boeing 777 program has taken a step further by developing a System Integration Laboratory (SIL) where for the first time all the airplane subsystems were fully integrated on the ground rather than on the aircraft [15]. The SIL is also sometimes called as the System Integration Platform (SIP). The SIP combined with the engineering flight deck simulator and standalone test benches provided a "service ready" aircraft at first delivery. The SIP was developed with the express objectives of conducting system-level tests to verify and debug subsystem interfaces. It also allowed airplane-level tests with all subsystems online, manufacturing and customer services tests. This helped to validate factory test procedures, maintenance and troubleshooting procedures. With modern aircraft subsystems becoming more and more integrated and coupled to each other, the advantage of a SIP to spot potential problems early in the design stages like design flaws (incorrect or incomplete requirements capture), incorrectly implemented requirements, interface mismatches etc. cannot be underestimated.

Every aircraft program begins with the concept stage followed by a preliminary design. The preliminary design is followed by analysis and detailed design phase leading to prototype development. The prototype aircraft may undergo redesign before it is released into service. The SIP, engineering simulators and the test benches must be maintained during the entire life cycle of the product including the support after entry into service. Therefore, the software and hardware of the platforms used in the Development Station (DS), Reconfigurable Engineering Simulator (RES) and SIP must be designed for maximum reusability. There are two aspects to the reusability. The first part is concerned with being able to quickly reconfigure a simulator to engineer or demonstrate different aircraft configurations which meet the same overall mission as already mentioned in the third paragraph of this paper. The second aspect of reusability involves using a substantial part of the hardware and software framework during the entire lifecycle of the aircraft development project. If both these aspects of reusability are factored into the design of the simulator framework, the aircraft program will benefit significantly in terms of the cost. Also a stable framework of tools helps development engineers to concentrate more on addressing the system design problems rather than learning new tools during the life cycle of the program. The Transport Research Facility (TRF) at NASA Langley Research Center is a good example of the simulation to flight concept approach [4]. The TRF consists of the Cockpit Motion Facility (CMF), Research System Integration Laboratory (RSIL), Flight System Integration Laboratory (FSIL) and the 757-200 flying testbed called Airborne Research Integrated Experiments System (ARIES). New concepts are first developed and tested in the CMF, RSIL and FSIL before they are flight tested on the ARIES.

Therefore, in summary simulators are capable of providing the means for system analysis, design and training of flight and ground crew. In addition, simulators are also increasingly used in the research of new concepts and as an educational tool [6, 16]. In the context of the next generation regional transport aircraft, simulators will play a key role in the form of Development Station (DS), Reconfigurable Engineering Station (RES) and SIP. These roles have been possible due to the rapid growth of computing power at low cost and the advancement of software engineering concepts [17] applicable to safety critical airborne software development. Modern languages permit Object Oriented Programming. Software Architectures have been evolved to provide Reuse / Rehosting [18-20]. Graphic based tools like Simulink allow for Model Based Design which promotes traceability between requirements and design and down to automatic code generation through the Real-Time Workshop [21]. In Table-1, the simulation support which can be provided at various stages in the design cycle is highlighted.

The concept of modeling and simulation is not just relevant to simulators alone, but is very powerful in the context of design and validation of individual systems [22-24]. The addition of optimization tools with mathematical models has resulted in the development of Multi Disciplinary Optimization (MDO) [25] as a tool for exploring the design space. Much research is still ongoing in MDO as problem formulation itself is a difficult part here. The choice of design variables, constraints, objectives, and models of the disciplines is not obvious. A further consideration is the strength and breadth of the interdisciplinary coupling in the design problem. A detailed discussion on MDO is beyond the scope of this paper. Therefore, modeling and simulation can play a key role when one or more of the following criteria are met:

- The system to be designed is complex with many interacting components
- The system requires integration of sub-modules belonging to multiple disciplines (i.e., it is a multi-physics problem)
- The system has many human machine interface design aspects which need to be resolved
- The CONOPS of the system requires a human being take decisions and actions in a predefined sequence to ensure safety to life and limb

The rest of the paper is organized as follows : In Section - Challenges in Aircraft Design, describes the complex challenges facing aircraft designers. It also desdribes the various stakeholders and how modeling and simulation helps each one of them to address the challenges arising from complexity. In Section - Status of Flight Simulation Technologies, the maturity of key simulation technologies is reviewed. The typical processes to be adopted to exploit modeling and simulation in aircraft design are also described in this section. Modeling and simulation as applicable to decision support during the different phases of an aircraft program are discussed in Section - Decision Support.. In Section - Simulators at

Table-1 : Modeling and Simulation Needs as Function of the Design Cycle

Design and Development Stage	Concept Definition	Detailed Design	Fabrication	Systems Integration	Flight Testing	Entry into Service	Post Entry into Service
Goals	Prototyping Design Concepts, Human Factors and Ergonomics	Design Validation : Functionality, Integration and Interfaces		Testing Aircraft Software and Hardware, Validating System Interfaces and Operation	Validation and Rehersal of Flight Test Plans, Certification Test, Maintenance Procedures	Aicraft Design Changes, Validation of Updates, Aircraft Derivatives, Pilot / Maintenance Training	
Simulation Support	Reconfigurable Simulators	Engineering Simulators		System Integration Platform	System Integration Platform, Maintenance Simulator	Full-flight Simulator, Maintenance Simulator	

CSIR-NAL, covers the progress made at CSIR-NAL on flight simulation in the past few decades. The conclusions are presented in Section - Conclusions.

Challenges in Aircraft Design

"The scientist discovers that which exists, the engineer creates that which never was" - Theodore von Karman.

"Design is what sets engineering apart from the sciences" - Dr. William Wilf, President of the National Academy of Engineering, U.S.A.

Engineering is about designing new products / technologies / processes which did not exist before. Engineering is primarily a creative process where the emphasis is on synthesis. Traditional engineering curricula however emphasize analysis. The industry has published a significant amount of literature on this subject [26-28]. Table-2 gives a brief comparison of the cultural difference between industry and academia.

Design of Complex Systems

The design of modem aircraft is further compounded due to complexity [26]. To give an example, the Boeing 777 has about 50,000 parts, 550 Suppliers and requires 50,000 manhours to build.

An aircraft is certainly a complex multi-disciplinary system [29]. Based on practical experience, many people argue that it is impossible to divorce aircraft design from the societal and psychological traits of individuals in the design teams [28]. In fact aircraft design has to be undertaken as a cooperative social activity by the various stakeholders involved. Each of the stakeholders has roles to play in the design process. Further, formal systems engineering approach is being proposed to meet these challenges [30]. The formal approach in traditional systems engineering consists of capturing a description of the system in terms of unambiguous written requirements. There are two drawbacks to this approach. Firstly, writing unambiguously requires a certain level of skill in abstraction on part of the engineer. Abstraction is required because the requirement as stated by the user needs to be stripped of unnecessary detail and made clear and concise in engineering terms. A requirement statement which has unnecessary detail can lead to preconceived or biased design choices. On the other hand, a requirement which is missing important details can leave too many design options open. In either case, the resulting miscommunication can be disastrous. In a large project, it becomes di ffi cult for any one person to determine if the requirements are consistent and complete. Secondly, unlike mathematical models, written requirements however well compiled, cannot be executed in the context of a scenario. The ability to execute a model allows us to evaluate what if analyses on the system. This capability also helps us to set up simulators for an aircraft and study many competing concepts well before we actually commit to deploying resources on the project. It is therefore not surprising that requirements based Systems Engineering is now augmented by mathematical models for handling large complex projects [31].

Table-2 : Industry Academia Culture (from [26])

Industry	Academia
Team oriented	Individual oriented
Liverage existing work	Create original work
Contribute to business	Contribute to science
Must produce	Must publish
Worthwhile market	worthwhile topic
Model specifics	Model fundamentals
Customer, customer, ...	Publish, publish, ...
For profit	Not for profit

The Design Team

A typical aircraft design and development activity will involve the following stakeholders:

- **The system architect or chief designer:** these are persons involved in the top level decision making like configuration design or system integration. It is desirable that such persons are "deep generalists" (deep knowledge in a few key technologies and breadth of knowledge in others) and tend to be synthesis oriented.
- **The sub-system designers:** these persons are responsible for the detailed technical design of a particular sub-system (e.g., hydraulics, electrical, flight control etc.) and are "technical specialists". These individuals need a good blend of synthesis and analysis skills.
- **The customer:** this person is the end user of the aircraft. Ignoring their concerns or involving them too late in the design phase can lead to serious time and cost escalations in the project.

Apart from the above, there is another category of stakeholder which can be loosely termed as "project managers". Persons in this category are typically involved in project management related to building the business case, budgeting and schedules. They are undoubtedly required in every major project. They do not play a direct role in the design and development process and are therefore not discussed in this paper further.

Yet another very important set of people involved in aircraft design belong to the certification authority. Every aircraft civil or military has to demonstrate compliance to flightworthiness regulations. In modern aircraft projects, the project office communicates to the airworthiness authority the Means of Compliance (MoC) that they intend to employ to meet mandatory regulations at the beginning of the project. The MoC is a statement of how each regulation will be demonstrated (i.e., by analysis, simulation, ground testing, flight testing etc.). The means of compliance is detailed down to each sub-system on the aircraft and linked chapter by chapter to the airworthiness regulations. Once the airworthiness authority gives an in principle approval to the Means of Compliance (MoC), the time and effort required for the entire certification process can be planned in advance. In this manner the certification process becomes closed ended. This approach works best when the critical technologies required for first flight have already reached a high level of maturity or when the critical technologies under development have a well thought out fall back plan in case of failure.

Time and cost overruns in a project can be avoided if correct risk assessment of the critical technologies required for a program is performed and the fall back options are prepared in advance.

Role of Stakeholders

The three primary stakeholders for the design process identified above have very distinct roles to play. Modeling and simulation technologies can assist in these roles in a major way:

- Chief designer: one of the first tasks of the design chief is to assess the feasibility of the proposed design. The trade-off is between system scope on the one hand and cost, quality, time and overall project risk on the other hand. In context of design projects, the risk is categorized in terms of likelihood of successful delivery of the final product given the current maturity levels of the various technologies involved. The trade-off studies can be carried out using mathematical models. The key lies in creating mathematical models at a suitable level of abstraction and using these to architect the system. The principle modeling and simulation tools available at this stage are top level system behavioral diagrams like activity diagrams, sequence diagrams and stateflow charts [31]. Modem languages like UML and SysML allow us to create these diagrams for complex projects in a collaborative'manner with different persons contributing to different aspects of the problem. This helps in early understanding of the top level specifications by all the stakeholders. As mentioned in the introduction MDO techniques allow the chief designer to better search the design space for a solution.
- Sub-system designer: each sub-system designer is responsible for the detailed design of their sub-system. Numerous multi-physics modeling and simulation tools are available which permit combined simulation of ODE's and PDE's. This allows the designer to determine for example the stress time history within a landing gear sub-assembly during a landing in cross winds. Such data previously would need specialized ground test rigs or actual flight testing to be conducted. Many of these tools are also interfaced with industry standard GAD / CAM tools as part of the product life cycle modeling, simulation and synthesis chain. This allows for creating CAD models, conducting kinematic studies and subsequently importing these models into PDE solvers for structural, fluid flow or multi-body dynamic analyses. Each of the multi-physics components can be prepared to a suitable level of model complexity based on the intended design clearance being sought. At detailed design stage, high fidelity models help in offloading some of the tests conducted in flight to the ground test rigs, saving development costs.
- Customer: the mathematical models of the sub-systems can be integrated into a simulator and presented to the user. Thereby the user can have an immediate appreciation of the design concept being proposed along with the concept of operation. A simulator permits the design team to run critical scenarios for evaluation. This allows for design changes to be made much earlier in the design cycle as opposed to later when the cost of these changes can be many multiples higher. For example, it is estimated that the cost of a design change made after the hardware has been built is up to 100 times that during the conceptual stage. By integrating sub-systems early in the design phase, the maturity of

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the design when the aircraft enters service will be higher leading to lower levels of customer complaints.

Thus, in large complex projects, the advantages of using system models for communication between the stakeholders and developing simulators for evaluating realistic scenarios should not be underestimated. This has been made possible by the development of subsystem models and simulation technologies outlined in the previous section. It is important to emphasize here that in the model based system engineering approach, the mathematical model of the subsystem is frequently used as a proxy in its place. Therefore, unless a mathematical model used in the design cycle is shown to be valid representation of the original sybsystem, its use can lead to erroneous conclusions or worse unsafe design decisions. In the next section we cover the various components of the flight simulator and the process to be adopted to create valid mathematical models during the aircraft design life cycle.

Status of Flight Simulation Technologies

A typical full flight simulator consists of the following components:

- Mathematical models simulating the basic flight physics and onboard sub-systems
- Displays and controls
- Visual system including synthetic image generation
- Control loading system to produce tactile cues
- Audio system to generate the aural cues
- Moving platform to generate motion cues

The technologies associated with the above components have reached a high level of maturity. In particular, generic mathematical models are available which can be configured to match the aircraft under study. The fidelity of each of the hardware and software components within a simulator is dictated by the purpose of the simulator.

If a scalable simulation framework / interface is provided, the generic models which are used in the preliminary design phase can be replaced by higher fidelity models in the detailed design phase ('plug and play'). The choice of a common modeling language / tool for various mathematical models encourages reuse of mathematical models across the project. A common Model Based Systems Engineering (MBSE) tool allows co-simulation of various subsystems thereby ensuring early integration of the subsystems.

Mathematical models encapsulate our understanding of the scientific phenomena relevant to a component in the form of equations. Each mathematical model has parameters which make the particular model Specific to a particular aircraft part. Thus, before using these models to help us in taking important decisions with regard to aircraft design it is necessary to validate the mathematical model. The areas of system identification,design of experiments and parameter estimation deal with this problem [32]. In some cases a first principles approach must be augmented with experimental data for validation. The experimental data can be produced in the ground based test rigs or by flight tests., The data may be in the form of a time or frequency responses to known inputs. Thus, validation of mathematical models will require coordination with the testing teams at various stages in the aircraft program to achieve the model fidelity appropriate at that stage.

In many aircraft programs, the traditional approach based on formal written requirements may be followed. A change over to the MBSE concept in such organizations may pose problems. The sub-system designer or domain experts may not be familiar with the MBSE tool chain for model development mandated within the organization. On the other hand, the apprentice engineers within the organization may be very adept with the MBSE tools but may lack the domain knowledge to develop and validate the models. Therefore, it is suggested that each sub-system designer be paired with the apprentice engineer who is skilled in the use of MBSE tools. The apprentice will generate valid mathematical models of the sub-system with the required level of fidelity under the supervision of the domain expert. This will help overcome the cultural resistance to MBSE if it exists, within the organisation.

Decision Support

Modeling and simulation has the ability to support and aircraft program at different stages from conceptualization to entry into service.

- **Preliminary** Design: At this stage, typically only system sizing data is available and therefore, generic model of the various subsystems already available within the simulator are used. The generic model will be populated with sizing information from the designers and integrated with the rest of the subsystems in a reconfigurable simulator. Critical aircraft level scenarios will be recreated in the simulator to validate the system sizing.

- **Detailed Design:** At this stage of the project, the various subsystems will have detailed designer's models available for purposes of simulation by the design teams. A simplified functional model will then be extracted using model reduction techniques and used in the simulator for scenario based design studies. This will help in developing the specifications for systems like the flight controls and avionics. The simulation models of the various subsystems will also be able to simulate failures as per defined requirements.
- **Prototype Development and Testing:** At this stage of the project, the subsystems developed to specifications are available for integration and testing. The simulator can then be expanded into a Hardware-in-Loop Simulator (HILS) with the Avionics, FCS, Hydraulics and IESVS systems in the loop. It is also possible to switch back to the high fidelity mathematical models in HILS depending on the type of test scenario being executed.
- **Flight Testing and Certification:** During this stage of the aircraft program, simulation models will be used for the playback of flight data to recreate incidents observed while flight testing. The replay or playback can be performed at the level of the subsystem or at the level of the aircraft as the case may be. It is proposed to develop the models based on clearly defined requirements. Therefore, it will be possible to trace the model features back to requirements. This will significantly reduce the certification effort.
- **After Entry into Service:** After entry into service, the aircraft will require training as well as maintenance simulators. Subsystem models developed for simulation on the reconfigurable simulator can be directly reused for this purpose.

A good approach to plan the modeling and simulation activities for an aircraft design project is to focus on the decision points like Preliminary Design Review (PDR) and Critical Design Review (CDR). Depending on the nature of the decisions required to be taken at these junctures, the overall scope of the modeling and simulation activities can be defined in a phase wise manner. The scope of work can be used to develop the requirements for the simulator and the underlying mathematical models. This will ensure that the mathematical models are designed and developed to the correct level of fidelity required for decision making at each stage.

Simulators at CSIR-NAL

Desktop Simulator for Educational Institutions

NALSim Desktop Simulator has being developed for aerospace engineering students to carrying out research in flight mechanics and control. This is achieved by closely coupling the simulation hardware to the' code generation, simulation, and analysis capabilities of Simulink and Matlab. The Simulator is designed for fixed wing, helicopter and a quad rotor and can be changed easily without the need for special programming skills. Models of standard disturbances like gust, cross wind and turbulence is built into the simulator. Control of the simulation is exercised from the console. Simulated flight operations are effected using off the shelf USB joystick (Fig.1). The System is designed around a single workstation with a high-end graphics adapter.

Engineer-in-the-Loop (ELS)

The ELS Simulator is in use extensively for LCA Tejas flight control law design, development and evaluation since 1993. The simulator has single window visuals with 40deg field of view horizontally and vertically (Fig.2). The basic aircraft dynamics equations are solved in real-time along with the flight control law and hydraulic system models. The system features a reprogrammable touch screen which can be used to rapidly reconfigure additional pilot control inputs.

SARAS Flight Training Device

The SARAS Flight Training Device (FTD) configuration corresponds to FAA Level 3 for Flight Training Device (FTD) with visual system corresponding to FAA Level A for simulators. The SARAS is a multi-role light category transport aircraft being designed by CSIR-NAL. The objectives of the SARAS FTD are:

- Familiarization of cockpit with its instruments, controls, switches and displays
- Training in normal and emergency procedures
- Training for takeoff, approach and landing
- Training on navigation, Stall, Auto-pilot modes

Important aircraft sub-systems such as Electrical, Fuel, Hydraulics, Air-Conditioning, Fire, ECS systems were developed and integrated to SARAS Simulator. Instructor System has been developed using which mal-functions can be initiated so that pilots can practice recovery procedures. The FTD uses Commercial-of-the-shelf (COTS) high-end computers, interface cards and equipment (Fig.3). The major features of FTD are:

- Replica of cockpit shell, mounted on a fixed base
- Replica flight controls, switches, knobs, levers, etc.,
- Replica instruments and displays
- Digital Electronic Controls loading for simulation of force feel on three axes. COTS high-end PCs, Monitors and interface cards

  Computer generated image (CGI) for the Out-of -the-Window visual system with three-channel projection display system
- Field of view (FOV) of 140 degrees in azimuth and 45 degrees in elevation
- Aural cues system for aerodynamics, engine, avionics, and other aircraft systems related sounds
- Intercom system between trainee and instructor
- Instructor Station (IS) to control and monitor pilot training
- Flying in normal mode including handling emergencies / malfunctions
- Simulation of avionics
- Simulation of Auto-pilot and Stall Warning System (SWS)

Augmented Engineering Environment

The Augmented Engineering Environment (AEE) for the RTA is a simulator established at NAL in joint partnership with CAE Inc., Canada and CAE India Pvt. Ltd. It consists of a DS and RES. The DS consists of desktop tools which allow the engineer to design prototype concepts for the displays. The RES is capable of providing support for design validation. The AEE developed by CAE is based on industry proven simulation scalable framework and system models. The RES is built on the Integrated Procedures Trainer (IPT) platform. The AEE also has a three window seamless edge matched visual system which is used to conduct piloted evaluations for the regional transport aircraft (Fig.4).

The reuse of hardware and software during the development phase leads to cost savings. In particular, the following systems of the aircraft will benefit from the AEE:

- Cockpit Ergonomics studies
- Pilot Vehicle Interface studies
- Flight Control System design and evaluation
- Integrated Enhanced and Synthetic Vision System design evaluation

The AEE is used for piloted evaluations of display symbology, control feel and FCS design aspects. It is also intended to be used for aircraft level Functional Hazard Analysis (FHA). The AEE will also provide the NAL research team a means to address any design level system integration issues with this facility.

Conclusions

The principal conclusions are as follows:

- Aerospace vehicles can be viewed as a complex multidisciplinary system
- Vehicle complexity is growing
- Modeling and Simulation can address issues arising out of system complexity
- Simulation tools are mature
- Mathematical models and simulators have to be designed to be "fit for purpose"
- Modeling and Simulation activities must be planned at the beginning of a program to maximize their effectiveness
- Scalable simulation framework for design and development is desirable
- Generic system models of aircraft subsystems with multiple levels of fidelity are required to help in the preliminary design stage
- Integrate early in the design cycle to eliminate costly changes later
- Integration of model based software development processes within the reconfigurable simulator will reduce overall certification time
- Optimization techniques can be combined successfully with modeling and simulation to improve the quality and efficacy of the design

- Finally, the thoughts presented are in the context of aircraft design. However, some of the ideas can be adopted to create a similar template for other complex, collaborative engineering design projects.

Disclaimer

The views expressed in this paper are those of the author alone and do not necessarily constitute the official position of any organization.

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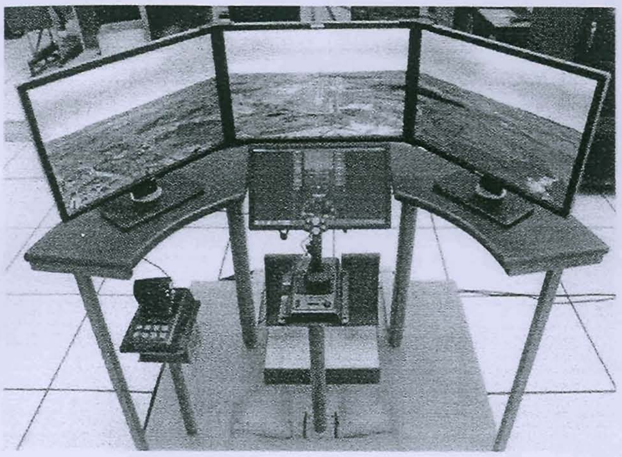

Fig.1 Desktop Simulator with Pilot Controls

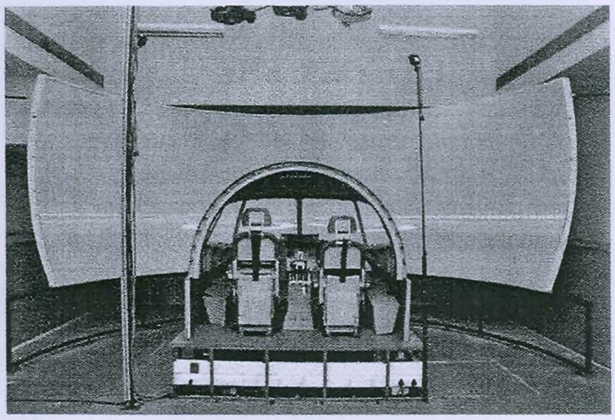

Fig.3 SARAS Flight Training Device

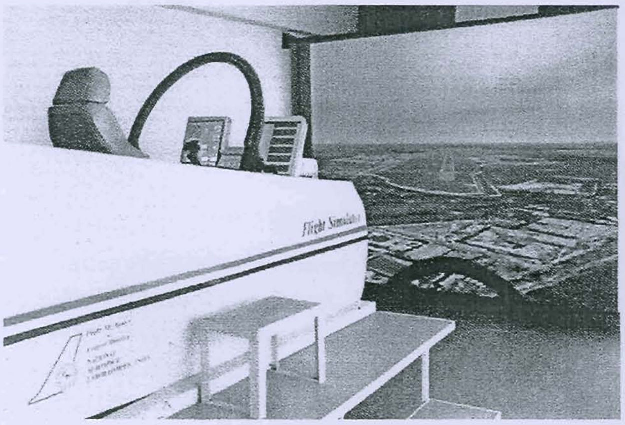

Fig.2 Engineer-in-the-Loop Simulator

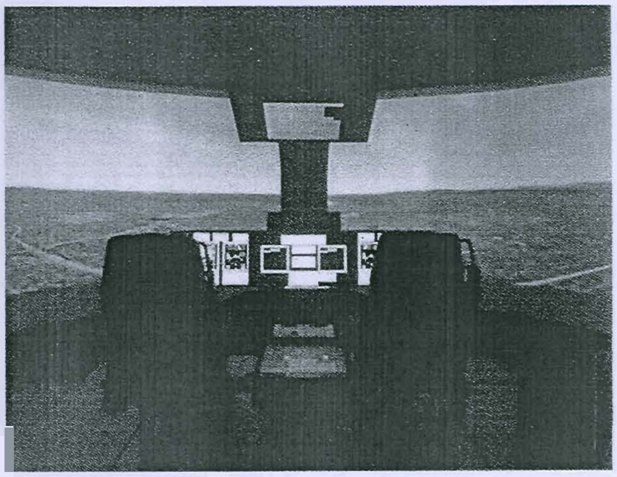

Fig.4 Augumented Engineering Environment for Regional Transport Aircraft